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V. K. Gupta and Ed Waymire

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This entire research effort was built on two mathematical themes which are necessary for a fundamental theoretical understanding of climate-hydrology-geomorphology interactions and for solving the practical problem of predictions from ungaged basins. These themes inclued (i) an ensemble view or a probabilistic framework, and (ii) self-similarity and scaling in space and/or time. This final report describes the main findings and progress separately under each objective. Keywords;

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FINAL REPORT

ARO PROPOSAL NUMBER: 21078-GS

TITLE OF PROPOSAL: Fundamental Studies on Basin Scale Hydrology

CONTRACT NUMBER: DAAG29-84-K-0064

NAME OF INSTITUTIONS: University of Mississippi and
                        Oregon State University

AUTHORS OF REPORT: V. K. Gupta and Ed Waymire

1. OBJECTIVES

The proposed research had two broad objectives.   These objectives, as

stated in the proposal, were:

(I)   Identify the 'geomorphologic laws' of drainage networks in three
      dimensions (i.e., taking into account both elevations and
      horizontal spatial dimensions) which determine the path of runoff
      to the basin outlet fed into the channel network from the adjacent
      hillslope regions and (b) undertake a theoretical representation
      of these 'laws' on the basis of a few general postulates.

(II) A coupling of the stochastic rainfall field in space-time with the
      basin scale response for investigating the statistical behavior of
      the streamflow process.

Dr. Gupta was the Principal Investigator in charge of the research on

Objective I, and Dr. Waymire, as a Sub-Contractor, on Objective II.

However, both Drs. Gupta and Waymire worked very closely on the entire

research effort.

2. MAIN FINDINGS AND RESULTS

This entire research effort was built on two mathematical themes

which are necessary for a fundamental theoretical understanding of

climate-hydrology-geomorphology interactions and for solving the

practical problem of predictions from ungaged basins.   These themes

include (i) an ensemble view or a probabilistic framework, and (ii) self-similarity and scaling in space and/or time. The following pages briefly describe the main findings and progress separately under each objective. However, throughout this research, our directions and progress on either one of the two objectives greatly influenced directions and progress on the other.

2.1. Objective (I)

Numerous empirical studies have shown that rivers shape their gradients in response to downstream increases (in a statistical sense) due to highly variable space-time flows and sediments in channel networks. Thereby they exhibit both 'random' and 'systematic' spatial variability. Our research on objective I was devoted to a theoretical understanding of this spatial variability in channel gradients because it provides the key to a theoretical understanding of connections between runoff production in river basins and channel network geometry, and predictiions from ungaged basins. We were led to rather unexpected and exciting findings as summarized below.

We developed a stochastic theory to test the statistical structure of spatial variability in link heights in channel networks. The topology of the channel networks is specified by the first postulate of the random model due to Shreve. We incorporated the systematic and random variability in link heights by formulating a notion of scaling invariance in their probability distribution functions (dfs) with respect to network magnitude (or drainage area) as a scale parameter. A non-random scaling function $\mu(m)$ of

magnitude m specifies the systematic variability. Theoretical predictions were tested against empirical observations by predicting a network structure function called the link concentration function (lcf). The lcf, denoting the number of links as a function of elevation, was introduced by Gupta, Waymire and Rodriguez-Iturbe [1986]. Four alternate sets of assumptions on $\mu(m)$ were tested using data from four basins from different climates and geologies. Rather unexpectedly, these tests led us to the discovery that link height dfs exhibit invariance under magnification or reduction of the scale parameter. This invariance property is referred to as 'statistical self-similarity'. It provides the following mathematical representation of the random height of a link of magnitude m in a channel network:

$$H(m) \overset{d}{=} m^{-\theta} H(1) , \tag{1}$$

where θ is a fundamental scaling exponent, and the symbol '$\overset{d}{=}$' in eq. 1 means that the random variables on both sides of it have the same dfs. Self-similarity provides a fundamental theoretical explanation of some purely empirical relationships regarding mean gradients and other geometries in channel networks. Preliminary formulations and tests of the above findings are given in Mesa [1986] and Gupta and Mesa [1988]. Detailed theory that led to this discovery is contained in Gupta and Waymire [1988].

2.1.1. <u>Generalizations of Self-Similarity and Prediction From Ungaged</u> <u>Basins</u>

We will briefly describe the issues concerning theoretical generalizations of self-similarity in link heights and gradients for channel network structures and peak flows in river basins. These generalizations have a direct bearing on predictions from ungaged basins. More details are given in Gupta and Waymire [1988].

Under the physically reasonable assumption of statistical independence between link gradients and link lengths, and the random model postulate on link lengths, it follows that link gradients in a channel network are also self-similar. The scaling exponents θ for link heights and link gradients are the same. Moreover, this exponent is <u>unique</u>. Let $s_\alpha(m)$ denote the α-quantile of a link gradient $S(m)$ of magnitude m, i.e., $P(S(m) > s_\alpha(m)) = \alpha$. It follows from self-similarity that,

$$s_\alpha(m) = s_\alpha(1) \, m^{-\theta} \tag{2}$$

Eq. 2 leads to a <u>fundamental theoretical explanation</u> that, purely empirical but widely observed, scaling of the means of link gradients, widths, etc., reported in the literature is due to self-similarity in these variables.

Beyond the means, the empirical relationship for quantiles of channel gradients and the theoretical relationship (2) <u>differ</u> in an important way. The empirically computed exponents for gradients are observed to vary with the frequency α, whereas the theoretical exponent θ in (2) <u>cannot</u> exhibit such a variation. Therefore,

tests of self-similarity in channel gradients and other geometries and peak flows were explicitly carried out in an M.S. Thesis by Cadavid [1988]. These tests clearly show that self-similarity is inadequate to describe the spatial variability in channel geometries and peak flows in a channel network. This feature would come about if link gradients in a network are not shaped by a single dominant flow frequency, but rather a whole spectrum of frequencies.

A theoretical generalization of self-similarity as a multiscaling invariance is needed before it can be tested from data for peak flows and link gradients in channel networks. A preliminary analysis of this kind for peak flows was carried out in an M.S. thesis by Cadavid [1988] with very encouraging results. However, the mathematical foundations of the multiscaling construct used in that thesis remain quite obscure. A precise formulation of multiscaling is not known and will require a lot more work. Should this line of investigation prove successful in the future, it would provide exciting new possibilities unthought of before towards flood predictions from ungaged basins and regionalization of flood frequency analysis.

2.2 Objective (II)

The space-time variability in peak flows and our speculation of a multiscaling property in it, suggests that these features , in a large part, are due to similar structures in space-time rainfall. In recent years, the evidence has been increasing that space-time rainfall exhibits scaling features; see, e.g., the special section on "Mesoscale Rainfall Fields" in J. Geop. Res., 92, D8, 1987.

Therefore, an understanding of such theoretical constructs becomes mandatory if we are to be able to understand how rainfall fields direct space-time variability in streamflows. Keeping in view this focus, we will _only_ summarize those results on rainfall which dealt with the scaling/self-similarity issues.

Self-similarity can arise most naturally as an asymptotic property under a wide variety of mathematical constructs. The ideas on scaling pertinent to rainfall were explained and illustrated by Waymire [1985] in an expository article.

Analysis of spatial rainfall from GATE data sets shows a scaling property in the second moment of spatially averaged rainfall. The averages are taken over regions ranging from 4 x 4 km^2 to 200 x 200 km^2. The same data sets have also been used to model the probability density of spatially averaged rainfall by a log-normal density. In Waymire and Gupta [1988] it was shown that self-similarity, defined in the usual sense of distribution functions, and lognormality are mutually _inconsistent_. This suggests modifications of self-similarity or lognormality, or both, for modeling spatial rainfall. Indeed, multi-scaling ideas are being explored by us and others in describingh space-time rainfall.

Finally, in an article by Gupta and Waymire [1987] it was shown that if a rainfall field is self-similar in space, then this property carries over in time via Taylor's hypothesis. This means that temporal rainfall becomes self-similar. However, the presence of dissipation in rainfall destroys Taylor's hypothesis after a time span of the order of a typical life cycle of a convective rainfall cell. This, in turn, leads to the conclusion that self-similarity in

temporal rainfall can manifest at most over a short time span but not beyond that.

3. LIST OF PUBLICATIONS

3.1 In Referred Journals

Rodriguez-Iturbe, I., V. K. Gupta, and E. Waymire, Scale Considerations in the Modeling of Temporal Rainfall, Water Resour. Res. 20(11):1611-1619, 1984

Valdes, J. B., I. Rodriguez-Iturbe, and V. K. Gupta, Approximations of Temporal Rainfall from a Multidimensional Model, Water Resour. Res. 21(8):1259-1270, 1985

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Gupta, V. K., and E. Waymire, Towards an Analytical Theory of Channel Gradients in Topologically Random Channel Networks, Submitted to Water Resour. Res., 1988 (Preprint).

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3.3 Theses and Dissertations for Advanced Degrees

Mifflin, E. R., On the Role of Network Geometry in Basin Response. M.S. Thesis, Dept. of Civil Engineering, The University of Mississippi, 1984.

Mesa, O. J., Analysis of Channel Networks Parameterized by Elevation, Ph.D. Dissertation, Dept. of Civil Engineering, The Univ. of Miss., 1986.

Cadavid, Eduardo E., Hydraulic Geometry of Channel Networks: Tests of Scaling Invariance. M.S. Thesis, Dept. of Civil Engineering, The Univ. of Miss., 1988.

4. LIST OF SCIENTIFIC PERSONNEL SUPPORTED

Vijay K. Gupta: P.I., University of Mississippi

Ed Waymire : Co-P.I., Oregon State University

Bao Nguyen : Visiting Research Professor, Univ. of Miss.

Oscar Mesa : Ph.D. Aug., 1986, Univ. of Miss.

Ed. Mifflin : M.S., Aug. 1984, Univ. of Miss.

Ed. Cadavid : M.S., Aug., 1988, Univ. of Miss.

Jaime Trujillo: Graduate Assistant, Univ. of Miss.

Vivek Kapoor : Graduate Research Asst., Univ. of Miss.

C. Subramanian: Undergrad Res. Asst., Univ. of Miss.

Scott Peckham : Graduate Res. Asst., Oregon State Univ.

Wang Xi : Graduate Res. Asst., Oregon State Univ.